Waste Management & Research

http://wmr.sagepub.com

Waste Minimization and Re-Use of Paper Sludges in Landfill Covers: a Case Study

Horace K. Moo-Young, Jr and Thomas F. Zimmie Waste Management Research 1997; 15; 593 DOI: 10.1177/0734242X9701500605

The online version of this article can be found at: http://wmr.sagepub.com/cgi/content/abstract/15/6/593

Published by: \$SAGE Publications http://www.sagepublications.com

On behalf of:

ISWA

International Solid Waste Association

Additional services and information for Waste Management & Research can be found at:

Email Alerts: http://wmr.sagepub.com/cgi/alerts

Subscriptions: http://wmr.sagepub.com/subscriptions

Reprints: http://www.sagepub.com/journalsReprints.nav

Permissions: http://www.sagepub.com/journalsPermissions.nav

9,4



WASTE MINIMIZATION AND RE-USE OF PAPER SLUDGES IN LANDFILL COVERS: A CASE STUDY

Horace K. Moo-Young Jr1 and Thomas F. Zimmie2

¹ Lehigh University, Bethlehem, PA 18015, U.S.A., ² Rensselaer Polytechnic Institute, Troy, NY 12180, U.S.A.

(Received 6 November 1995, accepted in revised form 30 April 1996)

This investigation attempted to find a beneficial use for waste water paper mill sludges by using paper mill sludges as the impermeable barrier in landfill covers. This study investigated the geotechnical properties of seven paper mill sludges for use as the impermeable barrier in landfill covers. Paper mill sludges have a high water content and a high degree of compressibility and behave like a highly organic soil. Consolidation tests reveal a large reduction in void ratio and high strain values that result from the high compressibility. Laboratory permeability tests were conducted on *in situ* samples, and these samples met the regulatory requirement for the permeability of a landfill cover. To determine the effectiveness of paper sludge as an impermeable barrier layer, test pads were constructed to simulate a typical landfill cover with paper sludge and clay as the impermeable barrier and were monitored for infiltration rates for 5 years. Long-term permeability values estimated from the leachate generation rates of the test indicate that paper sludge provides an acceptable hydraulic barrier.

Key Words—Waste minimization, re-use, paper sludge, landfill, impermeable barrier permeability.

1. Introduction

The elevating cost of waste disposal may be reduced by the use of unconventional material in the construction of landfills. The high price of disposal has sparked interest in the development of alternative uses for waste sludges (paper mill sludges and water treatment plant sludges). Paper mill sludges, in spite of high water contents and low solid contents in comparison to clays, can be compacted to a low permeability and can substitute for clays in landfill covers. Since 1975, paper mill sludges have been used to cap landfills in Wisconsin (Stoffel & Ham 1979; Pepin 1984; Aloisi & Atkinson 1990; Swan 1991; Zimmie & Moo-Young 1995). Moreover, since paper mill sludges are considered a waste product, they are provided to the landfill owner at little or no cost. This may reduce the cost of construction by U.S. \$20 000 to U.S. \$50 000 per acre. This study looks at the use of paper mill sludges as the impermeable barrier in landfill covers. It also investigates the geotechnical properties of seven paper mill sludges for use as the impermeable barrier in landfill covers; water content, specific gravity, organic content, consolidation characteristics, shear strength and compaction test. Test pads were constructed to simulate a typical landfill cover with paper sludge and clay as the impermeable barrier and were monitored for infiltration rates for 5 years.

Seven sludges were used in this study. Sludge A is a waste water treatment plant

Sludge	Water content (%)	Organic content (%)	Specific gravity	
A	150-230	45–50	1.88-1.96	
В	236-250	5060	1.83-1.85	
C1	255–268	50–60	1.80-1.84	
C2	183-198	45–50	1.90-1.93	
C3	222–230	40-45	1.96-1.97	
D	150–185	42–46	1.93-1.95	
E	150-200	40–45	1.86-1.88	

TABLE 1
Summary of water content, organic content, and specific gravity

sludge from a deinking recycling paper mill. Sludge B is a blended sludge from a wastewater treatment plant that receives its effluent from a recycling paper mill and the neighboring community. Sludge C is a blended sludge from an integrated paper mill and is composed of kaolin clay, wood pulp and organics. Sludge C was mined from a sludge monofill that has been in operation since 1973. Samples were collected from different sections of the monofill to represent different sludge ages: one week (C1), 2–4 years (C2), and 10–14 years (C3). Sludge D is a primary waste water treatment plant sludge from a recycling paper mill. Sludge E is a primary wastewater treatment plant sludge from a non-integrated paper mill that uses titanium oxide as the primary filler.

2. Materials and Methods

2.1 Geotechnical characteristics

Geotechnical classification of paper mill sludges is not like a typical clay used in landfill cover systems. Organic content, specific gravity, and water content are the major physical properties of sludges.

The ranges of natural water contents, organic content, specific gravity, and permeability are summarized in Table 1. Water content was determined according to American Society for Testing and Materials (ASTM) procedure D2974. The organic content of the paper sludge was determined according to ASTM procedure D2974, method C for geotechnical classification purposes. Specific gravity tests were performed on the sludges according to ASTM procedure D854. Paper sludges are characterized by a high initial water content and organic content in comparison to clays. Paper mill sludges are also characterized by a low specific gravity in comparison to clays.

2.2 Compaction characteristics

Proctor tests were performed following the ASTM procedure D698-78. Because of the high water content tests were conducted from the wet side rather than from the dry side, as recommended by ASTM. Furthermore, when water was added to dry sludge, large clods formed, the clods were difficult to break apart, and the sludge lost its initial plasticity. The sludge was passed through the number 4 sieve and placed in a pan to

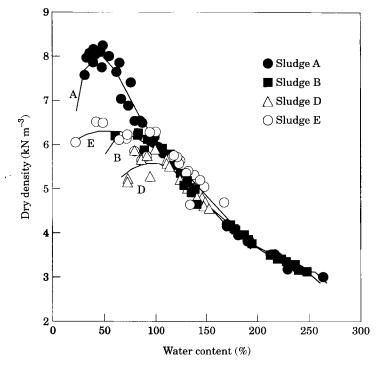


Fig. 1. Proctor compaction curves for various sludges (dry density versus water content).

air dry. Many trials were conducted to reach the optimum moisture content and density. Figure 1 shows the Proctor curve, optimum moisture content, and dry density for sludges A, B, D and E. (Compaction tests were not conducted on sludge C, since the compaction properties of most sludges are similar.) Proctor curves are skewed with only a small range of water content on the dry optimum side of the curves and with a wide range of moisture contents on the wet of optimum portion of the curve. At high water contents, the dry density obtained from the Proctor curve for the various sludges is similar (Sludge C should follow the same trend as sludge A, B, D, and E at higher water contents). At the optimum density and moisture content, the sludge is dry, stiff and unworkable. A very high water content is desirable, if the sludge is to be used as a landfill capping material (Zimmie et al. 1995). These test results compare favorably to research conducted on water treatment plant sludges (Raghu et al. 1987; Environmental Engineering 1989; Wang et al. 1991).

During the construction of the Hubbardston landfill in Hubbardston, Massachusetts and Erving Paper mill test plots in Erving, Massachusetts, U.S.A., different types of equipment were used to place the sludge cap. Four types of equipment were used: a small ground pressure vibratory drum roller, a vibrating plate compactor, a sheepsfoot roller, and a low ground pressure track dozer. The sheepsfoot roller that is generally used to compact a clay clogged immediately due to the cohesive nature of the sludge and the high water content. Vibratory methods did not provide homogeneous mixing and did not compact the sludge effectively. The small ground pressure dozer provided the best method for placement and compaction. This equipment successfully eliminated large voids from the sludge material and kneaded the material homogeneously.

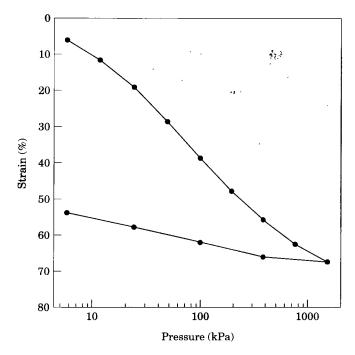


Fig. 2. Typical consolidation test result for sludge A.

2.3 Consolidation characteristics

One dimensional consolidation tests were conducted on all sludge samples following ASTM procedure D2435. Figure 2 displays the plot of strain versus the logarithm of pressure from a typical consolidation test run on paper sludge A. Test results show that paper sludge is highly compressible. At higher consolidation pressures, high strain values were measured. Low strains were encountered during the first increment. Large reductions in water content and void ratio resulted from application of higher applied stresses. These results compare favorably to consolidation test conducted on water treatment sludges (Raghu *et al.* 1987; Wang *et al.* 1991; Alvi and Lewis 1987).

2.4 Shear Strength Tests

The shear strengths of paper sludge A, B, C3 and D were determined using consolidated undrained triaxial compression tests with pore pressure measurements following ASTM procedure D4767. Tests were not conducted on sludge E, since sludge E was not used as a landfill cover. Table 4 summarizes the effective angle of internal friction, cohesion, and pore pressure parameter A results (pore pressure parameter A is defined as the ratio between the change in pore pressure and the change in major principle stress). These results compare favorably with those other researchers who conducted studies on water and wastewater treatment sludges (Wang et al. 1991; Alvi & Lewis 1987).

During the consolidation phase of the triaxial tests, a large reduction in void ratio resulted due to the high compressibility of the sludge. This behavior is consistent with that observed during the consolidation testing previously. Moreover, the values of $A_{\rm f}$ indicate that the sludges behaved similar to a normally consolidated clay.

TABLE 2				
Summary of shear strength	tests			

Sludge	Internal friction (Θ')	Effective angle of cohesion (kPa)	\mathbf{A}_{f}	
A	31	5.9	0.73	
В	37	5.5	0.9	
C3	32	9.0	0.7	
D	40	5.5	0.73	

TABLE 3
Summary of laboratory permeability tests on *in situ* samples

Sample	Hydraulic conductivity (cm s ⁻¹)	Water content (%)	
1	July 1991 1.06 × 10 ⁻⁷ October 1991	190	
2	4.0×10^{-8} April 1992*	185	
3	4.47×10^{-8}	106	
4	4.2×10^{-7} January 1993†	220	
5	3.4×10^{-8} July 1993‡	107	
6	3.8×10^{-8}	91.5	

^{*9} months

TABLE 4 Statistical data for estimated hydraulic conductivity data from 13 September 1989–23 July 1994. $(cm s^{-1})$

	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6
Average	2.3×10^{-7}	3.5×10^{-7}	3.5×10^{-7}	2.7×10^{-7}	1.6×10^{-7}	1.1×10^{-7}
Standard	4.8×10^{-7}	2.8×10^{-7}	3.0×10^{-7}	3.2×10^{-7}	1.8×10^{-7}	1.1×10^{-7}
Deviation						
variance	2.3×10^{-13}	8.0×10^{-13}	9.3×10^{-14}	1.0×10^{-13}	3.3×10^{-14}	1.2×10^{-14}
Range	4.1×10^{-6}	1.5×10^{-6}	1.5×10^{-6}	1.9×10^{-6}	1.0×10^{-6}	5.3×10^{-7}
Minimum	2.3×10^{-9}	1.7×10^{-8}	1.8×10^{-8}	7.9×10^{-9}	8.9×10^{-9}	2.7×10^{-9}
Maximum	4.1×10^{-9}	1.5×10^{-8}	1.5×10^{-8}	1.9×10^{-9}	1.0×10^{-9}	5.4×10^{-9}

Failure is difficult to determine from the stress-strain curves, which are typical of soft compressible material in that they exhibit no sharp yield point. Failure has to be arbitrarily selected at some reasonable strain. For the purpose of this study, failure is

^{† 18} months

^{‡24} months

defined at 10% strain. Obviously, if failure is defined at a different strain, the strength parameters would change. The variation in shear strength for the various sludges may be attributed to the wide range of water contents, to the variations in sludge production, and to the high organic content. Moreover, differences in the amount of fibers in the sludge matrix may alter the amount of cohesion measured in the paper sludge.

2.5 Laboratory hydraulic conductivity tests conducted on undisturbed samples

Laboratory hydraulic conductivity (permeability) tests were conducted on undisturbed sludge A samples taken from the Hubbardston Landfill on five occasions: July 1991, October 1991, April 1992, January 1993, and July 1993. Hydraulic conductivity tests were performed following the procedures of ASTM D5084 for measuring the hydraulic conductivity of saturated porous material using a flexible wall permeameter with back pressure. Samples were tested at a low confining stress of 34.5 kPa to simulate the worst case, that is the highest hydraulic conductivity.

The best sampling procedure was discovered through trial and error using Shelby tubes. Slow static pressure (pushing the Shelby tube into the sludge layer with a constant vertical force) compressed the sludge during the sampling process and led to low recovery rates. A dynamic sampling process, striking the sampling tube with a hammer, results in high rates of recovery and minimal disturbance. Apparently, due to the fibers and tissues in the sludge matrix, a sharp blow was needed to cut through the sludge. The normal field procedure was to place the Shelby tube on the sludge, place a wood block on top of the Shelby tube, and strike the block with a hammer. This procedure resulted in the highest rates of recovery and the least disturbance (Moo-Young 1992).

In general, the samples met the $1 \times 10^{-7} \, \mathrm{cm \, s^{-1}}$ regulatory requirement for a low hydraulic conductivity landfill cover system. Table 3 summarizes the hydraulic conductivity of the samples. The water contents of the specimens taken from the landfill after construction varied from 185% to 220%. All samples (1, 2 and 4) taken from various section of the landfill immediately after construction either met the regulatory requirements or were very close.

Sample 3, taken after 9 months, was dewatered and consolidated under an 18-inch (45.7-cm) overburden. It was markedly stiffer and denser than samples obtained shortly after construction. The hydraulic conductivity for sample 9 meets the regulatory requirements of 1×10^{-7} cm s⁻¹.

Sample 5 obtained in January 1993 was taken from the same section of the landfill as sample 3, 18 months after placement. Hydraulic conductivity tests yielded an average hydraulic conductivity of 3.4×10^{-8} cm s⁻¹ at a water content of 107%, which easily meets the 1×10^{-7} cm s⁻¹ standard for landfill cover design. After 18 months of consolidation the sludge layer met the regulatory requirements. The sludge layer performs as an adequate hydraulic barrier at a water content of 107% and a void ratio of 2.1. Sample 6 was taken 2 years after placement from the same section of the landfill as samples 3 and 5. Sample 6 meets the permeability requirement. Thus, time, dewatering, and consolidation have reduced the permeability of sludge A.

2.6 Test pad construction

In 1989, Erving Paper Mill alone conducted a study to establish the long-term hydraulic conductivity characteristics of paper sludge to obtain approval from the Massachusetts Department of Environmental Protection to use sludge A as a landfill capping material

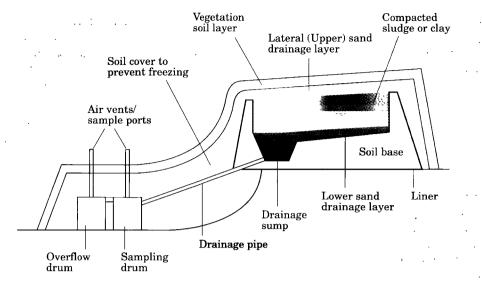


Fig. 3. Cross section of landfill test pads.

(Aloisi & Atkinson 1990). Six test pads simulating typical landfill covers were constructed of primary sludge A (test pads 2 and 3), clay (test pad 1), and blended sludge A (test pads 4, 5 and 6). (Primary paper sludge is from primary wastewater treatment; blended paper sludge is a combination of primary and secondary wastewater treatment.) The test pads are $7.62 \,\mathrm{m} \times 7.62 \,\mathrm{m}$ in area. Figure 3 shows the test pads set up. Fine-grained sandy soil (lower sand drainage layer) is used to prepare a smooth base with a 6% bottom slope and containment berms. A protective geotextile filter fabric covers the base of each test pad. The liner of the test pad consists of a 6-ml agricultural plastic. The leachate collection system consists of PVC piping and two plastic drums in series. The PCV pipe is secured to the liner with gaskets and clamps. A geotextile filtered solids from entering and possibly clogging the leachate collection system.

A (upper) lateral sand drainage layer (15.24 cm thick) was placed over the test pad liner system for the collection of leachate infiltrating through the overlying cap. A low hydraulic conductivity layer, either clay or paper sludge, was placed above the drainage layer. A 15.24-cm sand layer was placed above the low permeability to facilitate the lateral flow of rain water. A 30.5-cm layer of top soil was placed on top of sand layer for vegetative support. Test pad 1 was constructed with a 45.72 cm thick clay barrier, test pad 2 and 3 were constructed with a 45.72 and 91.44 cm thick primary sludge A barrier, and test pads 4, 5, and 6 were constructed of 45.72, 91.44 and 91.44 cm thick blended sludge A barriers, respectively. A low pressure ground dozer was utilized to compact the sludge layers into 21-cm lifts. Test pad 6 was constructed 1 year after the construction of test pads 1 to 5. Test pad 1 was constructed at an initial water content of 20%, and test pads 2 to 6 were constructed at a high initial water content ranging from 150–200%. Collection drums were emptied periodically to determine the amount of leachate generated.

2.7 Leachate generation

Figure 4 illustrates the cumulative leachate production through test pads 1, 2, 3, 4, and 5 over 5 years (13 September 1989 to 25 July 1994) and test pad 6 over 4 years (13

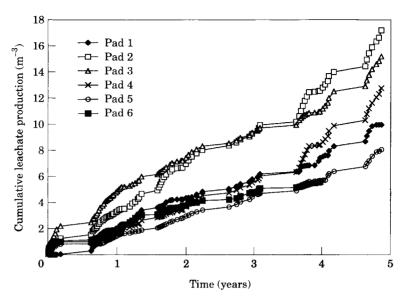


Fig. 4. Cumulative leachate production for each test pad.

September 1990 to 25 July 1994). The breaks in the data represent the winter months when snow covered the test pads and frozen ground conditions occurred. Analysis of the clay test pad (test pad 1) data in Fig. 4 reveals that after the installation during the fall of 1989, which is represented by 0 to 0.25 years, very little moisture percolated through the clay test pad. After the first winter, the clay control pad (test pad 1) generated greater quantities of leachate. The highest cumulative leachate production over the 5 years occurred through the 45.72-cm and 91.44-cm primary paper sludge test plots (test pads 2 and 3). The lowest cumulative leachate production occurs for the two 91.44-cm blended paper sludge test pads (test pads 5 over 5 years and test pad 6 over 4 years). After 5 years, the leachate production for test pads 5 was approximately 20% less than the clay control pad, and for test pad 6 the leachate production was approximately 16% less than the clay control pad. From this data, it appears that blended paper sludge provided a better hydraulic barrier than primary paper sludge, since the cumulative leachate production through the blended paper sludge barriers was much lower than the primary paper sludge barrier. Moreover, since blended paper sludge had a lower cumulative leachate production than the clay barrier after 4 to 5 years, it can be inferred that blended paper sludge provides a better hydraulic barrier than clay with time.

2.8 Estimated field hydraulic conductivity

Estimations of field hydraulic conductivity or percolation rate is based on the rearrangement of Darcy's law. (k = Q/iA where k is the field hydraulic conductivity, Q is the flow rate, A is the area of the best pad (58.1 m²), and i is the hydraulic gradient which equals the barrier thickness divided by the hydraulic head.) Assuming that the low hydraulic conductivity layer was fully saturated, the hydraulic head in the sand drainage layer was assumed to be negligible, and the hydraulic gradient was assumed to be one.

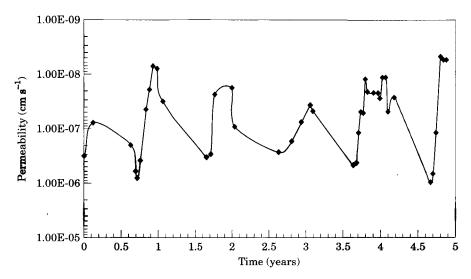


Fig. 5. Estimated hydraulic conductivity for test pad 1 (13 September 1989 to 25 July 1994).

An example of how to compute the hydraulic conductivity is as follows: if the area of the landfill cover is $58.1 \, \text{m}^2$, the thickness of the sludge layer 91 cm, the hydraulic gradient is one, and the inflitration rate (flow rate) through the cover is $10 \, \text{m}^3 \, \text{day}^{-1}$ ($1.16 \times 10^{-4} \, \text{m}^3 \, \text{s}^{-1}$), then the hydraulic conductivity through the cover is $2 \times 10^{-6} \, \text{m s}^{-1}$ ($2 \times 10^{-8} \, \text{cm s}^{-1}$).

Figure 5 shows the field hydraulic conductivity or percolation rate for test pad 1, the clay control, over the 5-year test period. (Table 4 shows the statistical data for each test plot which includes the average, standard deviation, variance, range, maximum and minimum values from 13 September 1989 to 25 July 1994.) Test pad 1 had an initial hydraulic conductivity of 3.2×10^{-7} cm s⁻¹. After construction in the fall of 1989 (fall, winter, spring and summer are represented by 0 to 0.25, 0.25 to 0.5, 0.5 to 0.75, and 0.75 to 1.0 years, respectively), there was decrease in hydraulic conductivity. An increase in hydraulic conductivity occurs after each winter. From Fig. 5, the increase in hydraulic conductivity occurred after 0.5, 1.5, 2.5, 3.5, and 4.5 years. For example, the permeability increased to a maximum value of $3 \times 10^{-6} \,\mathrm{cm}\,\mathrm{s}^{-1}$ during the spring (0.5–0.75 years) of year 1 (Fig. 5). Hydraulic conductivity increases in the clay test pad after the winter months (during the spring) may have been caused by ground freezing conditions (Aloisi & Atkinson 1990). During the summer and fall (e.g. 0.75 to 1.0 and 0.0 to 0.25 years), there is an improvement in the test pad's permeability to a value below the regulatory requirement of $1 \times 10^{-7} \,\mathrm{cm}\,\mathrm{s}^{-1}$. It can be postulated that the improvements in the field hydraulic conductivity of test pad 1 during the summer and fall may result from the closure of cracks caused by ground freezing.

Blended paper sludges have been used as the landfill cover material by various municipalities (Moo-Young 1995) and represents a realistic comparison to the clay barrier since it has a lower initial hydraulic conductivity in comparison to primary sludge (Moo-Young 1995). Figure 6 displays the estimated field hydraulic conductivity of test pad 5, the 91.44-cm blended sludge test pads, which represents the sludge test pad with the lowest cumulative leachate production. Test pad 5 is characterized by high initial permeability of $2.1 \times 10^{-6} \,\mathrm{cm \, s^{-1}}$, which is approximately one order of

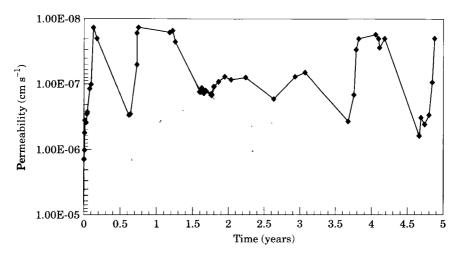


Fig. 6. Estimated hydraulic conductivity for test pad 5 (13 September 1989 to 25 July 1994).

magnitude higher than the clay test pad. Test pad 5 varies in a similar manner to the clay test pad. (i.e. there is an increase in hydraulic conductivity during the spring followed by a decrease in permeability during the summer and fall).

In comparison to the clay test pad (test pad 1), during the first year (0.0 to 1.0 years), test pad 5 (Fig. 6) showed an increase in permeability greater than the clay control (Fig. 5). Hydraulic conductivity changes are determined from the maximum and minimum values during a range of time. For example, during the first year, when comparing the maximum and minimum values, test pad 1 shows an increase in hydraulic conductivity of one order of magnitude (Fig. 5). Test pad 5 shows an increase of more than one order of magnitude during the first year (Fig. 6). During the first year, the maximum permeability for test pad 5 is less than the maximum permeability for test pad 1, which indicates that the paper sludge barrier is performing as a better hydraulic barrier in comparison to the clay, although there was a greater increase in hydraulic conductivity for the blend sludge test pad. During the second, third and fourth years, test pad 5 showed an increase in hydraulic conductivity less than the clay control (as shown in Fig. 5) which also indicates that the sludge A barrier performed as a better hydraulic barrier in comparison to the clay. The variance of test pad 5 is lower than the clay control which indicates that the estimated permeability for blended paper sludge A does not fluctuate as much as the clay test pad. Similar results were determined for test pads 4 (45.7-cm blended sludge) and 6 (91.4-cm blended sludge).

Figure 7 plots the estimated hydraulic conductivity results for test pad 3 (91.44 cm primary sludge A test pad). Test pad 3 has a high initial permeability of 5×10^{-6} cm s⁻¹. Test pad 3 follows the same trend as test pads 1 and 5 with an increase in hydraulic conductivity during the spring of each year. However, test pad 3 does not provide as effective a hydraulic barrier as test pads 1 and 5. For example, the minimum hydraulic conductivity values during each one year interval for test pad 3 (Fig. 7) is higher than the minimum permeability for test pads 1 (Fig. 5) and 5 (Fig. 6) during the same time. Test pad 3 (Fig. 7) also has a higher maximum permeability in comparison to test pads 1 (Fig. 5) and 5 (Fig. 6) during each 1-year interval.

Shelby tube specimens were taken from test pads 1 (clay control) and 5 (blended

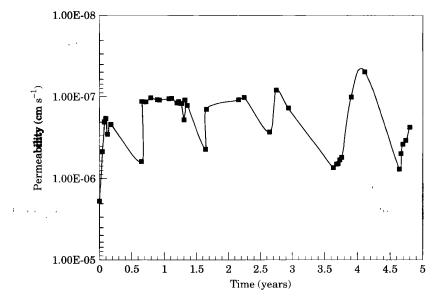


Fig. 7. Estimated hydraulic conductivity for test pad 3 (13 September 1989 to 25 July 1994).

sludge) approximately 3.75 years after construction. After 3.75 years, the clay test pad specimen was dry and stiff with an initial water content of 15% and a hydraulic conductivity of $1 \times 10^{-7} \, \mathrm{cm \, s^{-1}}$. From Fig. 4, in June 1993 (which represents 3.75 years), the hydraulic conductivity value for test pad 1 is approximately $9 \times 10^{-8} \, \mathrm{cm \, s^{-1}}$. Although the laboratory-measured hydraulic conductivity was slightly lower, this indicates a good correlation between the determination of the hydraulic conductivity in the field and in the laboratory.

After 3.75 years in situ, a specimen from test pad 5 had a final water content of 125% and laboratory-measured hydraulic conductivity of $1.1 \times 10^{-8}\,\mathrm{cm\,s^{-1}}$. From Fig. 5, in June 1993 (which represents 3.75 years), the hydraulic conductivity inferred from the infiltration data for test pad 5 is approximately $2.5 \times 10^{-8}\,\mathrm{cm\,s^{-1}}$, which is slightly higher than the laboratory-measured value. This shows a good correlation between the laboratory- and field-measured hydraulic conductivity (for this particular time of sampling). After 4 years, the organic content of test pad 5 decreased to 31%. Thus, from the laboratory permeability testing of in situ samples, it can be inferred that the blended paper sludge provides a better hydraulic barrier than the clay control. The clay control was dry and stiff which possibly increases its susceptibility to cracking if differential settlement was to occur. With dewatering, consolidation, and organic decomposition, blended paper sludge A provided a better hydraulic barrier than the clay used in this study.

If samples were taken at another time, the laboratory results may have varied relative to the *in situ* hydraulic conductivity inferred from the infiltration data. Laboratory hydraulic conductivity values obtained for test pads 1 and 5 may represent the lower limits of permeability, since Shelby tubes were used for sampling. [In comparison to the average hydraulic conductivity (Table 4), the hydraulic conductivity values from the Shelby tube samples for the paper sludge and clay are low.] Since no temperature measurements were taken of the test pads, there is no data indicating that freezing and

thawing occurred. Since sampling was conducted three months after the winter, there was no definite field evidence which indicated whether freezing and thawing had occurred.

If freezing and thawing did occur at the test pads, then the hydraulic conductivity of the test pads may have been higher. Chamberlain *et al.* (1995) showed that Shelby tube sampling disturbs the special macro- and micro-structure cracks caused by freezing and thawing on clay samples and that hydraulic conductivity values obtained by using Shelby tube specimens are lower than those obtained from using other methods (frozen core sampling and block sampling) which do not disturb the specimens structure.

3. Conclusions

- (1) Paper sludges are characterized by a high water content and organic content and a low specific gravity in comparison to typical clays. Paper mill sludges are characterized by high compressibility. Consolidation of paper mill sludges results in a large reduction in void ratio and water content.
- (2) Compaction tests were conducted from the wet side, since paper sludge loses its plasticity upon drying and rewetting. At the optimum moisture content, paper sludge is unworkable. A high water content is desirable when designing a paper sludge landfill cover.
- (3) The initial permeability values from a landfill that uses paper sludge as the hydraulic barrier either satisfy the regulatory requirements or are very close to the requirement. With time, dewatering and consolidation improve the permeability of a paper sludge hydraulic barrier.
- (4) Initially, the leachate production from the blended sludge test pad was greater than the leachate production from the clay test pad. As time increased, the leachate produced from the blended sludge test pad decreased.
- (5) After 5 years, the estimated permeability of the blended paper sludge was lower than the clay control.
- (6) With time, dewatering, and organic decomposition, the blended paper sludge provided a better hydraulic barrier than clay and primary paper sludge.

4. Acknowledgement

Support for this research was received from the following organizations: Erving Paper Company, Erving, MA; International Paper Company, Corinth, NY; Marcal Paper Mill Inc., Elmwood Park, NJ; Mead Speciality Paper Division, Lee, MA; Clough Harbour and Assoc., Albany, NY; and the Army Research Office, Research Triangle Park, NC. We would especially like to thank William Aloisi of the Erving Paper Company for his support in the preparation of this document.

References

- Aloisi, W. & Atkinson, D. S. (1990) Evaluation of paper mill sludge for landfill capping material. Prepared for Town of Erving, MA by Tighe and Bond Consulting Engineering, Westfield, MA, U.S.A.
- Alvi, P. M. & Lewis, K. H. (1987) Geotechnical properties of industrial sludges. *Environmental Geotechnology* (H. Y. Fang, ed.) Envo PC: Bethlehem, PA, U.S.A., pp. 57-76.
- Chamberlain, E. J., Erickson, A. E. & Benson, C. H. (1995) Effects of Frost action on compacted

- Clay Barriers. *GeoEnvironment 2000*, ASCE Geotechnical Special Publication No. 46 (Y. B. Acar & D. E. Daniel eds.), ASCE, New York, NY, U.S.A., Vol. 2, pp. 702–715.
- Environmental Engineering & Technology Inc. (1989) Water plant sludge disposal in landfills. Quarterly Report 1.
- LaPlante, K. (1993) Geotechnical Investigation of Several Paper Mill Sludges for Use in Landfill Covers. Master of Science Thesis, Rensselaer Polytechnic Institute, Troy, NY, U.S.A.
- Moo-Young, H. K. (1992) Evaluation of the Geotechnical Properties of a Paper Mill Sludge for Use in Landfill Covers. Master of Science Thesis, Rensselaer Polytechnic Institute, Troy, NY, U.S.A.
- Moo-Young, H. K. (1995) Evaluation of Paper Mill Sludges for Use as Landfill Covers. Ph.D. Thesis. Rensselaer Polytechnic Institute, Troy, NY, U.S.A.
- Pepin, R. G. (1984) The use of paper mill sludge as a landfill cap. *Proceedings of the 1983 National Council of the Paper Industry for Air and Stream Improvement (NCASI) Northeast Regional Meeting*, NCASI, New York, NY, U.S.A.
- Raghu, D., Hsieh, H. N., Neilan, T. & Yih, C. T. (1987) Water treatment plant sludge as landfill liner. Geotechnical Practice for Waste Disposal 87. Geotechnical Special Publication No. 13, ASCE, pp. 744–757.
- Stoffel, C. M., & Ham, R. K. (1979) Testing of high ash paper mill sludge for use in sanitary landfill construction. Prepared for the City of Eau Claire, WI, by Owen Ayers and Associates, Inc. Eau Claire, WI, U.S.A.
- Swann, C. E. (1991) Study indicates sludge could be effective landfill cover material, *American Paper Maker*, pp. 34–36.
- Wang, M. C., He, J. Q. & Joa, M. (1991). Stabilization of Water Plant Sludge for Possible Utilization as Embankment Material. Report, Department of Civil Engineering, The Pennsylvania State University, PA, U.S.A.
- Zimmie, T. F. & Moo-Young, H. K. (1995) Hydraulic Conductivity of Paper Sludges Used for Landfill Covers. In *GeoEnvironment 2000* (Y. B. Acar & D. E. Daniel eds.), ASCE Geotechnical Special Publication No. 46, New Orleans, LA, U.S.A., 2: pp. 932–946.
- Zimmie, T. F., Moo-Young, H. K. & LaPlante, K. (1995) The use of waste paper sludge for landfill cover material, *Green '93—Waste Disposal by Landfill*, (R. W. Sarsby ed.), Bolton Institute, Bolton, U.K., A. A. Balkema: Rotterdam, The Netherlands, pp. 487–495.

Subject of the control of the contro